A new tool for conjunction analysis of ISRO's operational satellites Close Approach Prediction Software: CLAPS

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ABSTRACT

During the lifetime of an operational spacecraft, a situation may occur when it faces a close approach with other orbiting space objects. The mitigation strategy for minimizing threat from orbiting space objects is to first carry out proximity analysis for operational spacecraft's (primary) with all other catalogued orbiting space objects (secondary). In case of a possible close approach, to plan an evasive collision avoidance maneuver. The ever-increasing number of space objects around the Earth demands this kind of analysis on daily basis by satellite operators. Presently, ISRO is operating close to 50 satellites in LEO and GEO/GSO orbits and this number is increasing each year at a rapid rate. At present the NORAD TLE catalogue consists of more than 18000 unclassified space objects. The large number of object pairs require enormous amount of computational load to do such kind of analysis on daily basis. Therefore, an efficient and user-friendly tool to predict the future close approaches is necessary for satellite operators.

In this paper, methodology is designed and developed for carrying out conjunction analysis for all operational satellites with catalogued space objects. In the design, efficient approach is adopted to reduce the computation time. Each object pair goes through screening process using pre-filters like perigee-apogee test and smart sieves. These filters are based on basic flight dynamics rules. Only those pairs which are passed by all filters are subjected to relative distance function method for finer assessment. For the candidate pairs which violate the specified minimum Inter-Satellite-Distance (ISD) limit, collision probability is computed. For operational satellites, latest available orbit determination results at control centre are used and orbit propagation is done with high fidelity ephemeris model. Orbit propagation of catalogued objects with TLE is done using SGP4 model. Using this design methodology, Close Approach Prediction Software (CLAPS) is developed in C++ language, to predict the future close approaches for multiple operational satellites with complete TLE catalogue in single run.

CLAPS s/w is tested for various close encounter cases and results are validated with STK's AdvCAT tool. The close approach time and minimum distance are found to match up to millisecond and millimetre level respectively. The results of few actual close approach scenarios are presented and discussed. CLAPS is being used regularly at ISRO's Master Control Facility, Hassan for routine monitoring of close approaches.

1. INTRODUCTION

Because of ever increasing number of objects in orbit around the Earth, evaluating the relative distance between two satellites is a routine requirement to support space missions. In close approach problems the satellite of interest is typically called the primary and the other object is called secondary. The task is to predict the time, two objects are within a specified relative distance, as well as the duration of the encounter, on the interval $t_n \le t \le t_{n+1}$. Upon predicting these encounters, orbital analysts can alert mission controllers of future close approaches, allowing them sufficient time to take corrective action. An obvious solution to close approach problems is to step sequentially along the orbits of two objects, then difference the position vectors to determine their relative distance; this approach is used to construct a truth table on encounters. The extent of evaluating close approaches ranges from a primary versus a single object to the limiting case of multiple primaries versus the entire object catalogue, which currently contains around 18000 objects. Although straightforward, the approach is computationally burdensome and this procedure consumes exorbitant amounts of computer processing time, especially if the number of candidate satellite becomes large. If we wanted to find all times of close approach for many primaries with all orbiting objects, the use of numerical technique become impractical. In literature, there are three classical pre-filters described by Hoots et al. [1] to eliminate many of the secondaries for further consideration based on orbit geometry information and basic flight dynamics principles. However, the drawbacks to this approach are the need for numerous trigonometric higher-order terms as well as an intelligent guess to start the Newton iteration. Other solutions have centred about the necessary and sufficient conditions of local minima and various iterative procedures to locate them. Typically, these techniques rely on numerical methods that might fail to converge in addition to being computationally expensive. On the other hand, the relative distance function method proposed by S Alfano [3] is free of any restriction on orbital motion, providing user a choice of analytical, numerical or hybrid propagators.

2. METHODOLOGY

The close approach analysis involves the study of inter-satellite distance (ISD) profile between primary (operational s/c) and secondary (other space objects) object pairs. For this each primary and secondary object pair orbit is propagated for specified analysis duration. The ISD profile is checked against a specified threshold. Orbit source can be either high fidelity ephemeris or NORAD TLE. A typical ISD profile variation is shown in Figure-1. The objective of close approach analysis is to identify global minimum ISD for all object pairs.

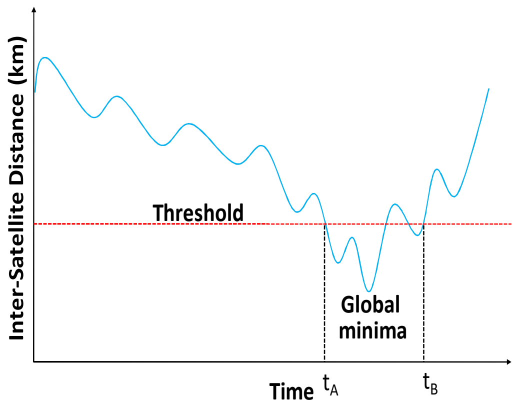

Fig. 1: ISD profile

Due to large number of objects in catalogue, computation load is enormous. To handle this, efficient pre-filters have been incorporated to eliminate many of the secondary for further consideration. Each object pair goes through screening using different pre-filters. There are three classical analytic filters in literature namely; perigee/apogee test, orbit path filter and time filter. These filters have the advantage of being easy to understand, but in practice they have been shown to be inadequate when implemented as originally described. Alfano et al. recommend using adding a pad to the detection threshold in Perigee/Apogee filter and sampling each trajectory at the beginning and end of the analysis interval to determine the range of radial distance for each object. The orbit path filter is seen to be the most troublesome of the classic filters. The associated computational benefit does not justify the additional effort required to improve the robustness of the filter. The recommendation of this paper is, therefore, to not use the orbit path filter. Out of the three classical filters, perigee/apogee test is simple and more robust. Another modern approach of pre-filtering is uses of Smart-sieve technique [2]. Both are incorporated in this methodology. These filters are described below in detail.

2.1 Perigee/Apogee filter

The Perigee-Apogee filter discards object pairs with altitude fringes separated by at least the specified threshold distance.

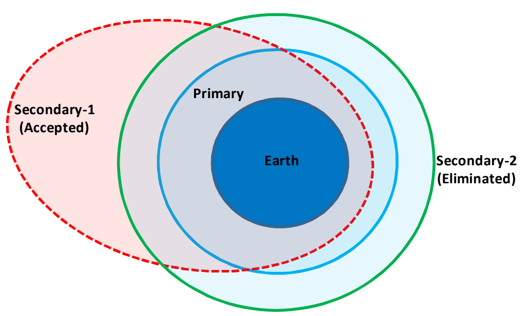

Fig. 2: Perigee/Apogee filter geometry

Many secondary objects can be eliminated from further consideration because the relative geometry of the pair of orbits does not allow the two trajectories to ever come within a specified threshold distance R_{th} . Let A denote the larger of the two perigees and B denote smaller of the two apogees. The secondary objects orbit will not come in close proximity to the primary if [1]

$$abs(A-B) > R_{th}$$

2.2 Smart-Sieve

Objects in elliptical orbits around the Earth can't exceed the so-called escape velocity v_{esc}. As a consequence, the relative velocity between two orbiting objects can never exceed twice the escape velocity. Using this principle, a conservative threshold distance for the sieve technique can be identified. If the initial distance to a critical area is higher than this, the object will not be able to enter the critical volume and get out of the threshold volume before the next check is performed. This principle is used in Smart-sieve filter [2].

At the time of close approach, the relative velocity vector is orthogonal to the miss vector, that is, the radius vector joining the positions of both encountering objects. The plane orthogonal to the relative velocity vector and containing both objects at the time of closest approach is called conjunction plane. The smart sieve technique consists of a series of filters based on very simple flight dynamics principles.

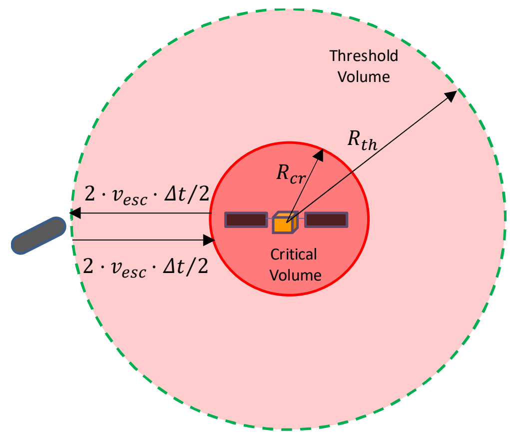

Fig. 3: Smart sieve geometry

Let us assume time step of duration Δt. A secondary object orbiting at twice the escape velocity over a time interval Δt would travel through a distance d_{esc}, given by

$$d_{esc} = 2 \cdot v_{esc} \cdot \Delta t$$

If the initial distance to a critical area is higher than $v_{esc} \cdot \Delta t$, the object will not be able to enter the critical volume and get out of the threshold volume before the next check is performed.

The corresponding threshold is given by

$$R_{th} = R_{cr} + \frac{1}{2} d_{esc} = R_{cr} + v_{esc} \cdot \Delta t$$

If two objects are separated more than R_{th} in any of the coordinate directions, they are more than R_{th} apart from each other. Let $\vec{\boldsymbol{r}} = \left(r_x, r_y, r_z\right)$ be the relative position vector of a pair of objects at any given sampling step. Then

$$R_i > R_{th} \Rightarrow r > R_{th} \qquad \text{for } i = x, y \text{ or } z$$

The efficiency of these sieves is very high as they require very few numerical operations and filter out a large number of objects.

An improvement is still possible in order to save computational time. If the distance between satellites turns out to be extremely large, some future sampling intervals can be skipped for the pair. The number of steps to be skipped is given by

$$N_{skip} = \mathrm{int}\left(\frac{r - R_{th}}{\sqrt{\left(\frac{\mu}{r_{p1}} + \frac{\mu}{r_{p2}}\right)} \cdot \Delta t}\right)$$

where r_{p1} and r_{p2} are the perigee radius of primary and secondary. This information can be easily stored in matrix form and checked before each sampling step.

To further reduce the computational load, ISD is not computed at every analysis interval step, instead the analysis is carried out using Relative Distance Function method. In this method the relative range vector function is approximated using cubic polynomial and close approaches are detected by finding real roots of this polynomial within an interval step, which is elaborated next.

2.3 Relative Distance Function method

An improved method for determination of close approaches was given by Alfano [3]. In this method cubic splines are used as approximating functions to determine minimum distance in closed form. Let $\vec{\boldsymbol{r}}_p$ and $\vec{\boldsymbol{r}}_s$ be the Earth-Cantered Inertial (ECI) position vectors of the primary and secondary objects, respectively, at time t. The relative distance vector and its time derivative become

$$\begin{aligned}
\vec{\boldsymbol{r}}_d &= \vec{\boldsymbol{r}}_s - \vec{\boldsymbol{r}}_p \\
\dot{\vec{\boldsymbol{r}}}_d &= \dot{\vec{\boldsymbol{r}}}_s - \dot{\vec{\boldsymbol{r}}}_p \\
\ddot{\vec{\boldsymbol{r}}}_d &= \ddot{\vec{\boldsymbol{r}}}_s - \ddot{\vec{\boldsymbol{r}}}_p
\end{aligned}$$

where the primary and secondary satellite vectors are provided by the user's orbit propagator or ephemeris. The distance function $f_d(t)$ and its time derivatives are defined by the dot products as given below

$$f_d(t) = \vec{\boldsymbol{r}}_d \cdot \vec{\boldsymbol{r}}_d$$

$$\dot{f}_d(t) = 2(\dot{\vec{\boldsymbol{r}}}_d \cdot \vec{\boldsymbol{r}}_d)$$

$$\ddot{f}_d(t) = 2(\ddot{\vec{\boldsymbol{r}}}_d \cdot \vec{\boldsymbol{r}}_d + \dot{\vec{\boldsymbol{r}}}_d \cdot \dot{\vec{\boldsymbol{r}}}_d)$$

Close approach to satellite occurs whenever $f_d(t)$ is at a local minimum; that is when $\dot{f}_d(t) = 0$ and $\ddot{f}_d(t) > 0$. To determine these times of closest approach, $\dot{f}_d(t)$ is represented by the range-rate polynomial equation $C_{\dot{f}_d}(\tau)$, where the subscript denote the function being approximated. The corresponding polynomial coefficients, are computed as

$$\begin{aligned}
\gamma_{\dot{f}_d 0} &= \dot{f}_d(t_n) \\
\gamma_{\dot{f}_d 1} &= \ddot{f}_d(t_n)\Delta t \\
\gamma_{\dot{f}_d 2} &= -3\dot{f}_d(t_n) - 2\ddot{f}_d(t_n)\Delta t + 3\dot{f}_d(t_{n+1}) - \ddot{f}_d(t_{n+1})\Delta t \\
\gamma_{\dot{f}_d 3} &= 2\dot{f}_d(t_n) + \ddot{f}_d(t_n)\Delta t - 2\dot{f}_d(t_{n+1}) + \ddot{f}_d(t_{n+1})\Delta t
\end{aligned}$$

Extract the real, distinct root(s) τ_{dROOT} of $C_{\dot{f}_d}(\tau)$ on the interval $[0,1)$. If no real root exists then no minimum is encountered during the time interval. If a real root does exist and

$$\left.\frac{dC_{\dot{f}_d}(\tau)}{d\tau}\right|_{\tau=\tau_{dROOT}} > 0$$, then a local minimum exists.

Only those object pair which passes through all the filters are subjected to the fine conjunction detection by Relative Distance method. Once the candidate object pairs are identified as a threat pair, the analysis is repeated with the latest state vector information of primary (and secondary, if available). For this full force model ephemeris access mode is also provided in CLAPS. Along with the fine conjunction detection process, the maximum collision probability is also calculated.

2.4 Collision Probability

Under the assumption that the relative position of the primary with respect to the secondary satellite is Gaussian distributed and the corresponding combined covariance matrix C is obtained, then, the three-dimensional probability density function (PDF) of the random variables x, y and z (the relative position denoted by $\mathbf{r}$) can be written as

$$f(x,y,z)=\frac{1}{\sqrt{8\pi^3|C|}}\exp(-\mathbf{r}^T C^{-1}\mathbf{r})$$

where $|C|$ denotes the determinant of C. Then, the probability of collision can be calculated by

$$P_c=\iiint_V f(x,y,z)\; dxdydz$$

Here V is the volume swept by a sphere with the combined radii of both objects through the space of the random variables. The computation of P_c is a dynamic 3D problem: the two objects are moving in 3-dimensions. However, it can be simplified by reducing the dynamic 3D problem to a static 2D problem. This is accomplished by performing calculations in the 2D conjunction plane. The conjunction plane is perpendicular to the relative velocity vector at the time of conjunction. The volume swept out by the combined spherical object is a cylinder (collision tube) whose axis is aligned along the relative velocity vector passing through the combined covariance ellipsoid. Projecting the tube onto the conjunction plane produces a circle whose radius is the sum of the radii of the two spherical objects. The projected covariance ellipsoid becomes an ellipse. This representation allows us to reduce the computational dimensionality from three to two. The resulting two-dimensional probability expression in conjunction plane [5] is given by

$$P_c=\frac{1}{2\pi\sigma_x\sigma_y}\int_{-r}^{r}\int_{-\sqrt{r^2-x^2}}^{\sqrt{r^2-x^2}}\exp\left[-\frac{1}{2}\left\{\left(\frac{x-xm}{\sigma_x}\right)^2+\left(\frac{y-ym}{\sigma_y}\right)^2\right\}\right]dydx$$

where r is the combined object radius, x lies along the covariance ellipse minor axis, y lies along the major axis, xm and ym are the respective components of the projected miss distance, and σ_x and σ_y are the corresponding standard deviations.

3. IMPLEMENTATION

Based on the above methodology, software is developed in C++ language and it can be run on Linux platform. There are three analysis modes in CLAPS: (1) TLE v/s TLE (2) SV v/s TLE and (3) SV v/s SV. In mode 1, both primary and secondary object's orbit propagation is done by SGP4 theory. In mode 2, the software accesses full force ephemeris for primary object's orbit propagation and secondary object orbit propagation is done using SGP4 theory. In mode 3, the software accesses full force ephemeris for both primary and secondary object. Mode 2 is the normal operational mode.

Presently CLAPS s/w is operational at ISRO's Master Control Facility and being used for close approach predictions on daily basis. The following figure depicts a typical CLAPS context diagram.

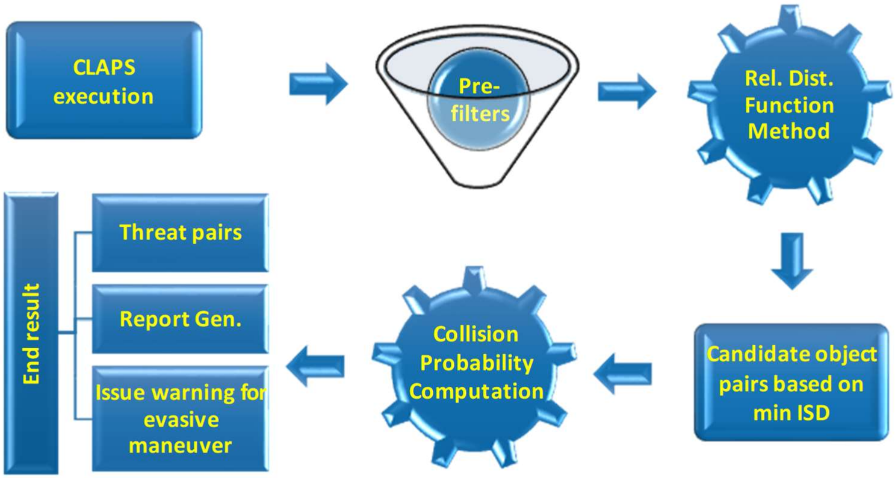

Fig. 4: CLAPS context diagram

4. TESTS AND VALIDATION

4.1 Case#1

On 06 October, 2018, a close conjunction between ASTROSAT and GAOFEN-1-04 was notified by SOPA (VSSC) [6]. This conjunction event is analyzed by CLAPS s/w and compared with SOPA results. The comparison in Table-1 shows that CLAPS results are very well matching with SOPA. The differences in ISD and close approach time are only 1 meter and 12 milliseconds respectively.

Table-1: Comparison with SOPA

Results	Close approach time (UT)	Min ISD (km)	Max Coll. Prob.
SOPA	2018-10-07 00:55:53.326	0.129	0.00144
CLAPS	2018-10-07 00:55:53.338	0.130	0.00136

4.2 Case#2

HysIS was scheduled for a launch onboard PSLV-C43 on 29 November, 2018. The nominal lift-off time was 04:27 UT. The actual lift-off time was delayed by 30 sec. Lift-off time is usually adjusted by Collision avoidance analysis (COLA) to avoid any close approach with other orbiting space objects during the ascent phase of the rocket or in injection orbit. Analysis has been carried out with CLAPS s/w by considering PSLV-C43 nominal separation parameters to assess the close conjunction scenario with all other catalogued space objects after injection. The analysis shows that there was a close approach with HysIS orbit and NOAA-6. The predicted minimum distance is **323 meters**. However, with the modified lift-off time, a similar analysis shows that there were no predicted close approaches within **1 km** range.

Table 2: CLAPS results

Lift-off time (UT)	Object (NORAD ID)	Close approach time (UT)	Min ISD (km)
2018-11-29 04:27:00.000	NOAA-6 (43295)	2018-11-29 15:36:35.065	**0.323**
2018-11-29 04:27:30.000	No object within 1 km		

4.3 Case#3

Close approach for all ISRO's operational GEO/GSO satellites was analyzed with complete NORAD TLE catalogue on 27 Feb 2019. CLAPS s/w was executed in mode 1 with 20 km ISD threshold.

TLE source: www.space-track.org
Analysis start: 2019-02-27 00:00 UT, Duration: 7 days
Total 29 GEO/GSO satellites are considered as primary objects. The catalogue consists of 17921 objects. On execution, CLAPS processed 519709 object pairs out of which only 161 pairs were passed by pre-filters for fine conjunction detection. 519519 objects pairs were eliminated by pre-filters. Among 161 object pairs, 39 close approaches were predicted within 20 km ISD threshold. Out of 39, only 5 close approaches were with other space objects and remaining all 34 close approaches were within Indian GEO satellites. Validation of results was done with STK's AdvCAT tool and results are in agreement up-to millimeter in ISD and millisecond level in close approach time. The comparison for all 5 close approaches is provided in Table-3.

Table 3: Comparison with STK AdvCAT

Primary Object (NORAD ID)	Secondary Object (NORAD ID)	CLAPS Results		STK AdvCAT Results	
		Close approach time (UT)	Min ISD (km)	Close approach time (UT)	Min ISD (km)
INSAT-3D (39216)	SYNCOM-2 (00634)	2019 03 01 18 24 14 083	10.706	2019 03 01 18 24 14 021	10.706
GSAT-7A (43864)	KUPON (25045)	2019 03 01 22 17 28 576	6.804	2019 03 01 22 17 28 612	6.804
GSAT-18 (41793)	RADUGA-23 (19928)	2019 02 28 20 05 01 055	16.375	2019 02 28 20 05 01 010	16.375
	RADUGA-28 (21821)	2019 02 28 20 42 51 387	19.002	2019 02 28 20 42 51 334	19.002
GSAT-19 (42747)	INDOSTAR-1 (25050)	2019 03 05 12 28 05 473	14.745	2019 03 05 12 28 05 460	14.745

4.4 CLAPS efficiency

Table-4 provides the results of computation time for the GEO case. The machine used for the analysis was Intel(R) Xeon(R) CPU E5-1607 v3 @ 3.10GHz on Red Hat Enterprise Linux 7.2 server. The analysis duration is 7 days. Results show that the present method is 99.96% more efficient than the brute force computation. The total numbers of close approaches were exactly identical to the brute force method.

Table 4: CLAPS efficiency

Method	Computing Time	No of close approaches
Brute Force (Without any filter)	97 hrs 8 min 34 secs	39
With Filters	2 min 12 sec	39

5. CONCLUSION

An efficient tool is developed for carrying out close approach analysis for all operational satellites with complete TLE catalogue. The results show that this s/w predicts all the close approaches accurately with high efficiency. The same methodology is proposed to be implemented at the upcoming SSA control center for daily monitoring of satellite close approaches

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